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Comparative Analysis of THOR-NT ATD vs. Hybrid III ATD in Laboratory Vertical Shock Testing

by Dmitriy Krayterman

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14. ABSTRACT

The Hybrid III dummy is a common standard test device for automotive car crash and mine blast (shock) events, which is validated and accepted by the crash test community. The Hybrid III 50th percentile male Anthropomorphic Test Device is also required by STANAG 4569 for injury assessment for mine detonation tests. The Test Device for Human Occupant Restraint (THOR) 50th percentile male advanced crash dummy is a next generation anthropomorphic test device that incorporates significantly improved biofidelity in all major parts and has expanded injury assessment capabilities beyond its predecessors, including the Hybrid III Anthropomorphic Test Device. Comparative evaluation of THOR versus Hybrid III dummies will bring additional insight and understanding of THOR injury prediction capabilities and biofidelity, specifically for vertical shock and mine blast events.

15. SUBJECT TERMS

vertical shock, drop test, crew protection, Hybrid III Anthropomorphic Test Device, THOR Anthropomorphic Test Device

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1. Introduction

Crash test mannequins, or dummies, are mechanical anthropomorphic test devices (ATDs) that simulate the dimensions, mass distribution, and articulation of the human body and are instrumented to record time dependent data about the dynamic behavior of the ATD in simulated vehicle impacts. An ATD is placed in a vehicle that is subjected to frontal, side, rear impact, or rollover event, and parameters such as velocity, force, moment, acceleration, etc., that are recorded. This data can be used to assess occupant injury, restraint systems, and motion dynamics in motor vehicle accidents.

The ATDs currently available are designed to mimic human behavior and respond to loads similarly to a human occupant in most common automotive accidents. In military applications these devices are also subjected to blast loads and consequent slam-down events that are not typical for automotive applications. These loads produce forces and accelerations mostly in a vertical direction, which available ATDs are not specifically designed to predict.

Currently, the Hybrid III 50th percentile male ATD manufactured by Humanetics, Inc. is a common standard test device for automotive frontal crash. This mannequin, representing an average male, is validated and accepted by the automotive crash test community. It is commonly used for mine blast (vertical shock) events by the military community (Aberdeen Test Center, MD) and is required by NATO STANAG 4569 for injury assessment for mine detonation tests.

In order to enhance the number of parameters recorded, the dynamic response, and the accuracy of responses, or biofidelity, of the Hybrid III dummy, the National Highway Traffic Safety Administration (NHTSA) funded the development of an advanced ATD. The next generation dummy that incorporates improved biofidelic components and expanded instrumentation was developed by GESAC Inc.; it is the Test Device for Human Occupant Restraint (referred to as THOR).

The original version of THOR ATD is called THOR Alpha and the later model with additional enhancements is called THOR-NT. The THOR ATD represents the weight of the 50th percentile male.

1.1 THOR Improvements Over Hybrid III

THOR Alpha major improvements in biofidelity and instrumentation[1] over Hybrid III are:

- Load sensing face with regional measurement capability

[1] Haffner, M.; Rangarajan, N.; Artis, M.; Beach, D.; Eppinger, R.; Shams, T. et al. Foundations and Elements of the NHTSA THOR Alpha ATD Design. Paper #458 in 17th International Technical Conference on the Enhanced Safety of Vehicles. HS 809 220 (U.S. DOT, 2001).

- Multidirectional head/neck design with kinematic performance matched to human impact data, and distinct cervical column and "muscular" load paths
- Human-like thoracic structure with clavicle representation, multiple high-speed 3D deflection instruments and optional mid-sternum unidirectional displacement measurement
- Articulating spine with adjustable vehicle-seated posture
- Pelvis design with revised anthropometry and flesh configuration, injury assessment capability at the hips, and submarining detection features

Additional minor modifications to THOR Alpha in anthropometry, durability, usability, and biofidelity were implemented during the development of the THOR-NT[2]. Some of them are summarized in the following:

- **HEAD** modifications:
    - integrated head skin that covered the skull and the face,
    - improved chin anthropometry,
    - zippered connection between head and neck skins,
    - improved mounting of the nine-axis accelerometer package, extended chin support.
- **NECK** modifications:
    - using injection molding to make the neck instead of bonding,
    - implemented new joint with continuous resistance in flexion and extension,
    - improved neck load cells,
    - the neck springs to include rubber inserts.
- **THORAX** modifications:
    - adding locating pins on the spine for attaching the ribs,
    - change of the jacket shape for better interface with the seat back.
- **SPINE** modifications:
    - using injection molding for making the thoracic and lumbar flex joints,
    - removing ribs features used for routing of the cables,

[2] Shams, T.; Rangarajan, N.; McDonald, J.; Wang, Y.; Platten, G.; Spade, C.; Pope, P.; Haffner, M. Development of THOR-NT: Enhancement of THOR Alpha–The NHTSA Advanced Frontal Dummy. Paper #455 in 19th International Technical Conference on the Enhanced Safety of Vehicles. HS 809 220 (U.S. DOT, 2005).

- easier assembly of the T1 triaxial accelerometer.

- **PELVIS** modifications:
  - changing the skin material to polyvinyl chloride (PVC) from urethane,
  - making the skeletal part of the pelvis of modular components instead of single cast piece.

- **LOWER LEG and FOOT** modifications:
  - adding clearance for the tibia puck fasteners to prevent puck binding when compressed,
  - improved retention of the foot skin to the foot plate.

1.2 Study Objective

The THOR-NT biofidelity and instrumentation improvements are clearly beneficial for the automotive crash community. However, there is no quantitative comparison between the advanced THOR-NT ATD and standard Hybrid III ATD for military applications that involve vertical shock representative of mine blast and slam down loads.

Comparative evaluation of the THOR-NT versus the Hybrid III dummy will bring additional insight and understanding of THOR injury prediction capabilities and biofidelity specifically for vertical shock and mine blast events.

2. Test Hardware

2.1 Vertical Shock Machine

A vertical shock machine is used to generate impulses representative of underbody blast loading. The test specimen is placed on the platform, lifted to a predetermined height, and then released to fall down under gravity. The resulting impact generates change in acceleration and velocity that is representative of the live fire blast event. The impact and rebound are measured as the velocity change (ΔV) (figure 1).

The vertical shock machine used in the experiment was a Lansmont Corporation (Monterey, CA) model 65/81 (figure 2). The pulse duration is controlled by varying stiffness and number of elastomeric bumpers between the table and the seismic mass. In free fall mode, the Lansmont 65/81 is capable of producing ΔV up to approximately 10 m/s.

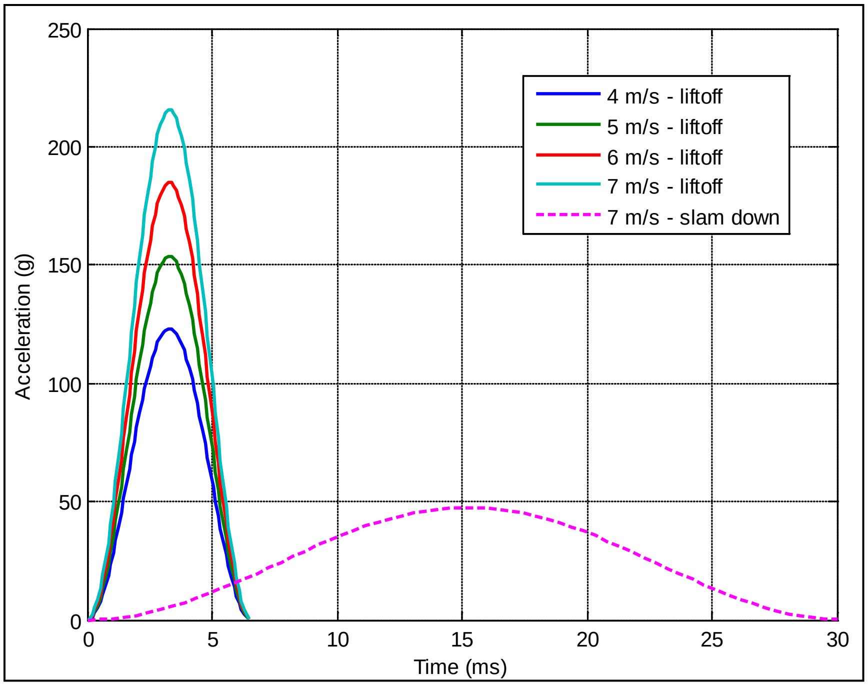

Figure 1. Representative test pulses.

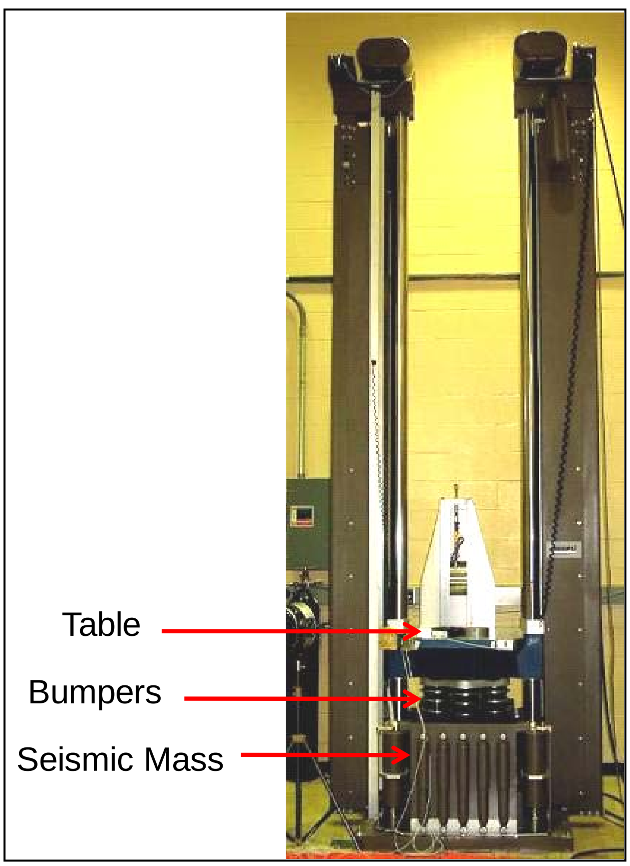

Figure 2. Vertical shock machine.

2.2 The Two Anthropomorphic Test Devices (ATDs)

1. The 50th percentile FTSS, Inc. (Plymouth, MI) Hybrid III ATD.
2. The 50th percentile GESAC, Inc. (Boonsboro, MD) THOR-NT ATD.

Both ATDs are in new condition. They have not been extensively used prior to this experiment (figure 3).

Figure 3. FTSS, Inc., Hybrid III (left) and GESAC, Inc., THOR ATD (right).

2.3 Rigid Test Fixture

The rigid test fixture is designed to create a rigid support for the ATD. This support is intended to transfer load from the drop tower platform to ATD with minimal energy loss due to elastic/plastic deformation thus providing the most pure ATD response to the shock. The fixture is designed to fit the drop tower platform and provide maximum rigidity with minimal weight.

The rigid test fixture is assembled with Faztek, LLC (Fort Wayne, IN) aluminum beams and plates bolted together with a 0.5-in-thick aluminum plate as a seat pan and a 0.25-in-thick aluminum plate as a back plate. Four-point seat belt restraints are attached to the top and sides of the fixture (figure 4).

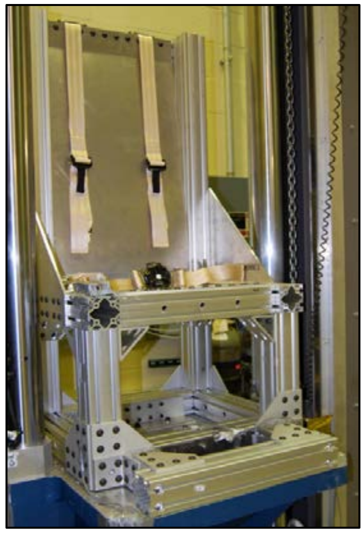

Figure 4. Rigid test fixture.

2.4 Instrumentation

Endevco Corporation 7270A-2K accelerometers were used to record input to the drop tower platform. A Spectral Dynamics VX2824 Data Acquisition System with up to 24 channels was used for data acquisition. All data was sampled at 125 kHz and filtered at 1000 Hz with an SAE J211 Channel Frequency Class filter.

2.5 High-Speed Video

High-speed video was captured with a Miro 4 black and white high-speed camera, sampling 1000 frames per second and with a Vision Research Phantom V9.1 (Wayne, NJ) high-speed video camera, sampling 1000 frames per second.

3. Experimental Procedure

3.1 Test Setup

The test setup consisted of the following steps:

1. The rigid test fixture was placed on top of the vertical shock machine and attached to the platform with screws.
2. The ATD (Hybrid III or THOR) was positioned in the rigid fixture with its back barely touching the seat back plate and articulated to be straight up and perpendicular to the seat plate.
3. All seat belt restraints were fastened lap belts and followed by tightening of the shoulder straps. All belts were tightened by the same operator to ensure consistency in belt tightening and routing application.

4. The legs of the ATD were placed on the leg support beam and secured with tape to ensure that they do not separate from the fixture during freefall. The arms were articulated to place the hands on the knee.

5. Tags describing the test conditions were placed on the ATD and still images were taken both pretest and post-test for each test event (figure 5).

Figure 5. Rigid fixture placed on the drop table with ATD seated: Hybrid III (left), THOR (right).

3.2 Drop Tests

The drop tests were designed to simulate live-fire load conditions that could be experienced by an occupant placed in a seat that may or may not have energy absorbing capabilities. Two pulse durations were selected: 5 ms and 20 ms. The 5-ms pulse represents a short duration, high acceleration, blast event that would be typical for a seat without energy attenuation capabilities, while the 20-ms pulse shock represents a longer duration, lower acceleration impact that would be typical for a seat with some energy attenuation capabilities or a slam down event.

Three conditions were investigated for each duration: ΔV 3, 4.25, 5.5 m/s or corresponding drop heights 10, 19, and 30 in. The maximum ΔV was selected so that resulting forces/accelerations do not impart severe damage to the ATD and it does not require consequent repairs and resets. The intermediate ΔVs were selected to have constant difference of 1.25 m/s between steps. The pulse shape is a single-sided haversine acceleration time histories.

The 10- and 30-in drops were repeated two times to insure reproducibility of the test. Since the original tests were performed at a different time than the repeated tests, the test fixture had to be reassembled for the repeated tests. The variation in fixture assembly (bolt pretension) could negatively affect the reproducibility of the tests.

Overall, for each ATD, 14 drop tests were performed.

A total of 28 drop tests were completed. They are summarized in table 1.

Table 1. Test data summary table.

Duration (ms)	~ΔV m/s	Drop hight (in)	# of drops
5	3	10 (2 repeats)*	3
5	4.25	19	1
5	5.5	30 (2 repeats)*	3
20	3	10 (2 repeats)*	3
20	4.25	19	1
20	5.5	30 (2 repeats)*	3

*The 10- and 30-in drops were repeated two times to insure reproducibility of the test. The first test was performed at a different time than the later two repeats due to unavailability of the test fixture. The fixture had to be reassembled for the repeated tests.

3.3 Analysis

3.3.1 ATD Instrumentation and Responses to be Acquired

Both Hybrid III and THOR ATDs have similar instrumentation throughout. Multiple load cells and accelerometers are placed in the main body parts of an ATD (figure 6) to measure loads, moments, and accelerations versus time to provide load histories in three degrees of freedom. These load histories are analyzed and compared to established injury criteria for each body part to determine injury nature and severity.

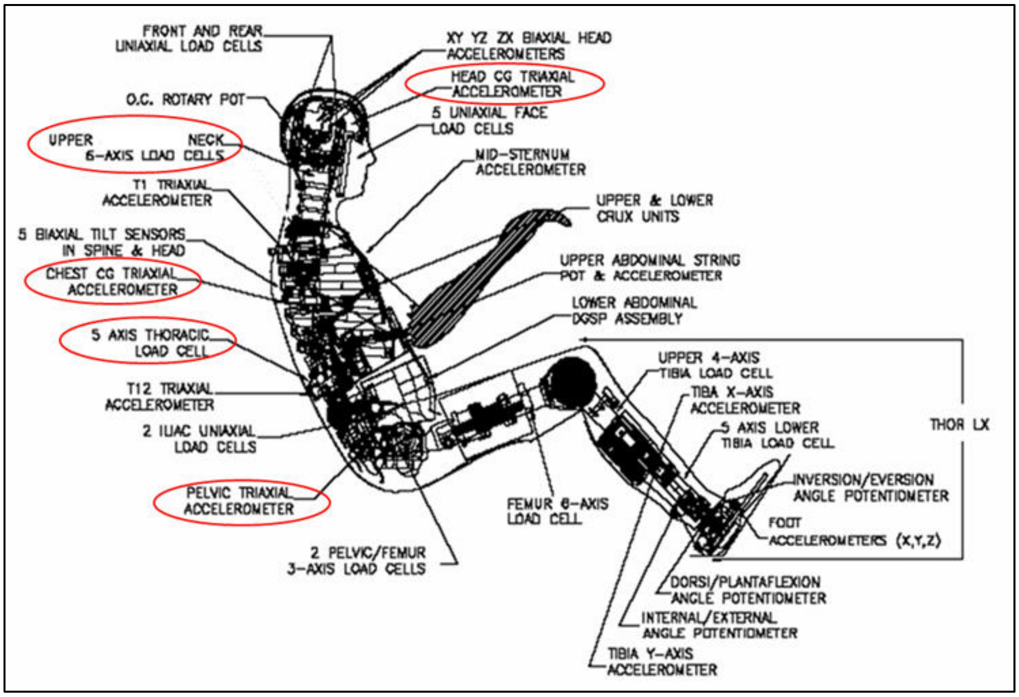

Figure 6. THOR ATD available instrumentation scheme with the U.S. Army Research Laboratory's (ARL) THOR instrumentation shown in the red ovals.[2]

The instrumentation (accelerometers and load cells) by body region for ARL THOR 50th percentile male ATD and Hybrid III 50th percentile is summarized in tables 2 and 3, axis notation is shown on figure 7.

Table 2. ATD Accelerometers (Endevco).

Body Part	**Hybrid III**			**THOR**		
	A_x	**A_y**	**A_z**	**A_x**	**A_y**	**A_z**
Head	X	X	X	X	X	X
Thorax (chest)	X	X	X	X	X	X
Pelvis	X	X	X	X	NA	X

[2] See footnote 2 on page 2.

Table 3. ATD Load cells (Denton).

Body Part		Hybrid III						THOR					
		F_x	F_y	F_z	M_x	M_y	M_z	F_x	F_y	F_z	M_x	M_y	M_z
Neck	Upper	X	X	X	X	X	X	X	X	X	X	X	X
	Lower	X	X	X	X	X	X	X	X	X	X	X	X
Spine	Thoratic	X	X	X	X	X	X	X	X	X	X	X	X
	Lumbar	X	X	X	X	X	X	NA	NA	NA	NA	NA	NA
Tibia	Right Leg	X	X	X	X	X	X	NA	NA	NA	NA	NA	NA
	Left Leg	X	X	X	X	X	X	NA	NA	NA	NA	NA	NA

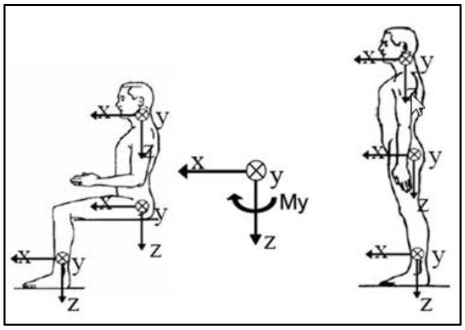

Figure 7. ATD axis notation.

The main interest for this experiment was to measure and compare Hybrid III's to THOR's vertical (z) response due to its dominance in blast induced loads. The vertical response is not commonly analyzed in automotive impact cases due to relative insignificance to injury mechanism. Each load and/or acceleration component represents one channel in the data acquisition system. Only the channels, mostly vertical load components that are dominant in blast and slam down events were acquired. The number of channels acquired was also limited to optimize post processing and data analysis time and effort. Table 4 summarizes channels, body locations, data types (force, moment, or acceleration) where time histories were recorded.

Table 4. Summary of data channels acquired.

Location	Thor		Hybrid III	
	# of channels	channel description	# of channels	channel description
Spine	3	Fx, Fz, My	3	Fx, Fz, My
Upper Neck	4	Fx, Fy, Fz, My	4	Fx, Fy, Fz, My
Pelvis	1	Az	1	Az
Head	2	Ay, Az	2	Ay, Az
Thorax	1	Az	1	Az
Total channels	11		11	

Where, F = force, M = moment, A = acceleration, x, y, z = axial components according to the axis notations shown in figure 7.

In addition to time histories acquired the dynamic response index is calculated and analyzed. The dynamic response index (DRI_z) is the standard metric for spine compression injury, which is the primary injury mechanism in vertical impacts. The vertical pelvis acceleration time history (A_z) is used to calculate DRI_z. For additional information, see the DRI definition in appendix A.

4. Results and Observations

4.1 Results Summary

Tables 5 and 6 summarize the results of all drop tests performed for both Hybrid III and THOR ATDs. The peak values from recorded load histories are provided in these tables. For repeated tests, the mean peak values and standard deviations are calculated and percent difference is provided for comparison. Neck force X, neck force Y, and head acceleration Y components did not register significant values and were not reported in the tables. Only the peak values are reported; the actual time histories are provided in appendix B.

Table 5. Hybrid III vs. THOR drop test results summary (maximum values), 5-ms pulse duration.

drop height (in)		10 in										
ATD TYPE		H3					THOR					mean %diff
		test 1	test 2	test 3	mean	st. dev	test 1	test 2	test 3	mean	st.dev	
spine	fx (lb)	468	387	337	397	66.1	227	252	294	258	33.9	**35**
	fz (lb)	1467	1478	1394	1446	45.7	1261	1230	1272	1254	21.8	**13**
	my (lb-in)	797	868	786	817	44.5	1176	913	973	1021	137.8	**-25**
neck	fz (lb)	353	386	368	369	16.5	281	276	284	280	4.0	**24**
	my (lb-in)	189	186	111	162	44.2	64	52	66	61	7.6	**63**
pelvis	az (g)	91	68	67	75	13.6	41	38	36	38	2.5	**49**
head	az (g)	39	38	39	39	0.6	26	25	26	26	0.6	**34**
thorax	az (g)	45	42	38	42	3.5	37	30	31	33	3.8	**22**
DRI		10	10.3	10.3	10.2	0.2	9.7	10.4	10.6	10.2	0.5	**-0.3**
table dv (left) (m/s)		2.9	3	3	3.0	0.1	2.9	3.1	3.2	3.1	0.2	**-3.4**

drop height (in)		30in										
ATD TYPE		H3					THOR					mean %diff
		test 1	test 2	test 3	mean	st.dev	test 1	test 2	test 3	mean	st.dev	
spine	fx (lb)	801	719	735	752	43.5	594	647	635	625	27.8	**17**
	fz (lb)	3016	3093	3196	3102	90.3	2111	2317	2370	2266	136.8	**27**
	my (lb-in)	2052	2064	2064	2060	6.9	1543	1222	1238	1334	180.9	**35**
neck	fz (lb)	690	740	753	728	33.3	453	530	543	509	48.6	**30**
	my (lb-in)	403	351	310	355	46.6	90	89	80	86	5.5	**76**
pelvis	az (g)	187	171	202	187	15.5	76	100	106	94	15.9	**50**
head	az (g)	79	81	83	81	2.0	42	49	50	47	4.4	**42**
thorax	az (g)	92	91	97	93	3.2	63	77	73	71	7.2	**24**
DRI		15.8	17.5	17.3	16.9	0.9	17.1	17.7	17.8	17.5	0.4	**-4.0**
table dv (left) (m/s)		5	5.5	5.3	5.3	0.3	5.3	5.3	5.5	5.4	0.1	**-1.9**

drop hight (in)		19 in		
ATD TYPE		H3	THOR	mean %diff
		test 1	test 1	
spine	fx (lb)	689	451	**35**
	fz (lb)	2097	1766	**16**
	my (lb-in)	1169	1433	**-23**
neck	fz (lb)	480	384	**20**
	my (lb-in)	290	76	**74**
pelvis	az (g)	138	71	**49**
head	az (g)	55	36	**35**
thorax	az (g)	63	55	**13**
DRI		13.9	13.4	**3.6**
table dv (left) (m/s)		4	4.1	**-2.5**

Table 6. Hybrid III vs. THOR drop test results summary (maximum values), 20-ms pulse duration.

drop height (in)		10 in										
ATD TYPE		H3					THOR					mean % diff
		test 1	test 2	test 3	mean	st. dev	test 1	test 2	test 3	mean	st.dev	
spine	fx (lb)	469	409	418	432	32.4	327	346	332	335	9.8	**22**
	fz (lb)	1311	1468	1424	1401	81.0	1294	1340	1441	1358	75.2	**3**
	my (lb-in)	713	808	730	750	50.7	1145	962	1050	1052	91.5	**-40**
neck	fz (lb)	326	383	361	357	28.7	280	307	320	302	20.4	**15**
	my (lb-in)	162	159	121	147	22.9	64	59	67	63	4.0	**57**
pelvis	az (g)	50	52	52	51	1.2	42	38	40	40	2.0	**22**
head	az (g)	35	37	39	37	2.0	26	28	29	28	1.5	**25**
thorax	az (g)	34	37	37	36	1.7	36	33	36	35	1.7	**3**
DRI		12	11.9	11.8	11.9	0.1	11.3	11.5	11.9	11.6	0.3	**2.8**
table dv (left) (m/s)		2.9	3.3	3.8	3.3	0.4	3.1	3.2	3.4	3.2	0.2	**3.4**

drop height (in)		30in										
ATD TYPE		H3					THOR					mean % diff
		test 1	test 2	test 3	mean	st.dev	test 1	test 2	test 3	mean	st.dev	
spine	fx (lb)	1173	958	913	1015	139.0	708	761	778	749	36.5	**26**
	fz (lb)	2445	2814	2815	2691	213.3	2228	2513	2671	2471	224.5	**8**
	my (lb-in)	1698	1906	2068	1891	185.5	1520	1241	1480	1414	150.9	**25**
neck	fz (lb)	589	676	696	654	56.9	501	580	603	561	53.5	**14**
	my (lb-in)	340	280	260	293	41.6	94	103	97	98	4.6	**67**
pelvis	az (g)	128	130	122	127	4.2	78	84	94	85	8.1	**33**
head	az (g)	67	72	74	71	3.6	47	52	55	51	4.0	**28**
thorax	az (g)	72	73	78	74	3.2	67	72	76	72	4.5	**4**
DRI		21.5	20.2	20.5	20.7	0.7	20.1	19.8	19.9	19.9	0.2	**3.9**
table dv (left) (m/s)		5.3	5.3	5.4	5.3	0.1	5.2	5.2	5.6	5.3	0.2	**0.0**

drop height (in)		19 in		
ATD TYPE		H3	THOR	% diff
		test 1	test 1	
spine	fx (lb)	785	550	**30**
	fz (lb)	1894	1815	**4**
	my (lb-in)	984	1314	**-34**
neck	fz (lb)	448	411	**8**
	my (lb-in)	303	83	**73**
pelvis	az (g)	92	62	**33**
head	az (g)	50	38	**24**
thorax	az (g)	52	52	**0**
DRI		16.7	15.9	**4.8**
table dv (left) (m/s)		3.7	3.9	**-5.4**

4.2 Observations

1. Vertical (z) forces and accelerations comparison:

   The Hybrid III shows higher maximum forces and accelerations than the THOR-NT in all of the tests in the vertical directions (z). The maximum force and acceleration difference between the Hybrid III and the THOR ATD is higher for the 5-ms pulse duration than for the 20-ms pulse duration (table 7).

Table 7. Mean percent response difference between Hybrid III and THOR ATDs for major body parts, 5- and 20-ms pulse duration.

pulse duration (msec)	5			20		
drop height (in)	10	19	30	10	19	30
Spine Fz (lbf)	13	26	27	3	4	8
Neck Fz (lbf)	24	20	30	15	8	14
Pelvis Az (g)	49	49	50	22	33	33
Head Az (g)	34	35	42	25	24	28
Thorax Az (g)	22	13	24	3	0	4

2. Dynamic response index (DRI) comparison (table 8):

Table 8. Dynamic response index (DRI) comparison.

Drop Heights	10 in			19 in			30 in		
ATD TYPE	Hybrid III	THOR	Mean % diff	Hybrid III	THOR	Mean % diff	Hybrid III	THOR	Mean % diff
5-ms pulse DRI	10.2	10.2	–0.3	13.9	13.4	3.6	16.9	17.5	–4
20-ms pulse DRI	11.9	11.6	2.8	16.7	15.9	4.8	20.7	19.9	3.9

- Measurements of the DRI do not show significant differences (less than 5%) between the Hybrid III and THOR ATDs for all pulse durations and drop heights.

- The DRI for the 20-ms pulse durations is consistently higher than the DRI for the 5-ms pulse duration for both ATDs.

- The 30-in drops (20 ms) resulted in DRI values higher than the injury limits of 17.7 specified in STANAG 4569 for both Hybrid III and THOR ATDs. Refer to the data in red in table 8.

3. The spine X force, Neck Y moment show different trends between Hybrid III and THOR; other measurements show similar trends
4. The test results from 1st and 2nd repeated drop tests conducted in February 2009 for 10- and 30-in drops seem to be closer to each other, while test results from the original drop tests conducted in August 2008 remain farther apart.

5. Conclusions and Recommendations

The THOR ATD produces significantly lower peak force and acceleration responses in the vertical direction for all major body parts for the short duration vertical shock compared to the Hybrid III ATD. For the longer duration pulse the THOR ATD also produces lower peak force and acceleration responses in the vertical direction, but not by such significant amounts as with the shorter duration pulse

Overall, for the longer duration pulse the THOR force and acceleration measurement are closer to those of the Hybrid III than for the short duration.

The DRI values obtained from pelvis acceleration are similar between the THOR and the Hybrid III ATDs and do not seem to be affected by the difference in peak pelvis acceleration. That is due to the effect of the pulse duration that is longer for the THOR ATD

The DRIs obtained for the shorter pulse durations are smaller than the DRIs obtained for the longer pulse durations

Test table delta V values were within 5.5% difference (maximum), which indicates a good repeatability of the test machine

The difference in response between the repeated tests for the 10- and 30-in drops conducted in February 2009, and the original tests conducted in August 2008, is most probably due to minor changes in assembly of the rigid fixture. Since the fixture had to be reassembled for the repeat tests, it is possible that some minor changes, such as variation in bolt preloading, occurred.

It is recommended to compare THOR predictions to post mortem human subjects (PMHS) in order to correlate the significance of these measurements.

It is also recommended to review/adjust the current injury criteria to enable the use of the more biofidelic THOR-NT ATD in test applications.

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Appendix A. DRI$_z$ Definition

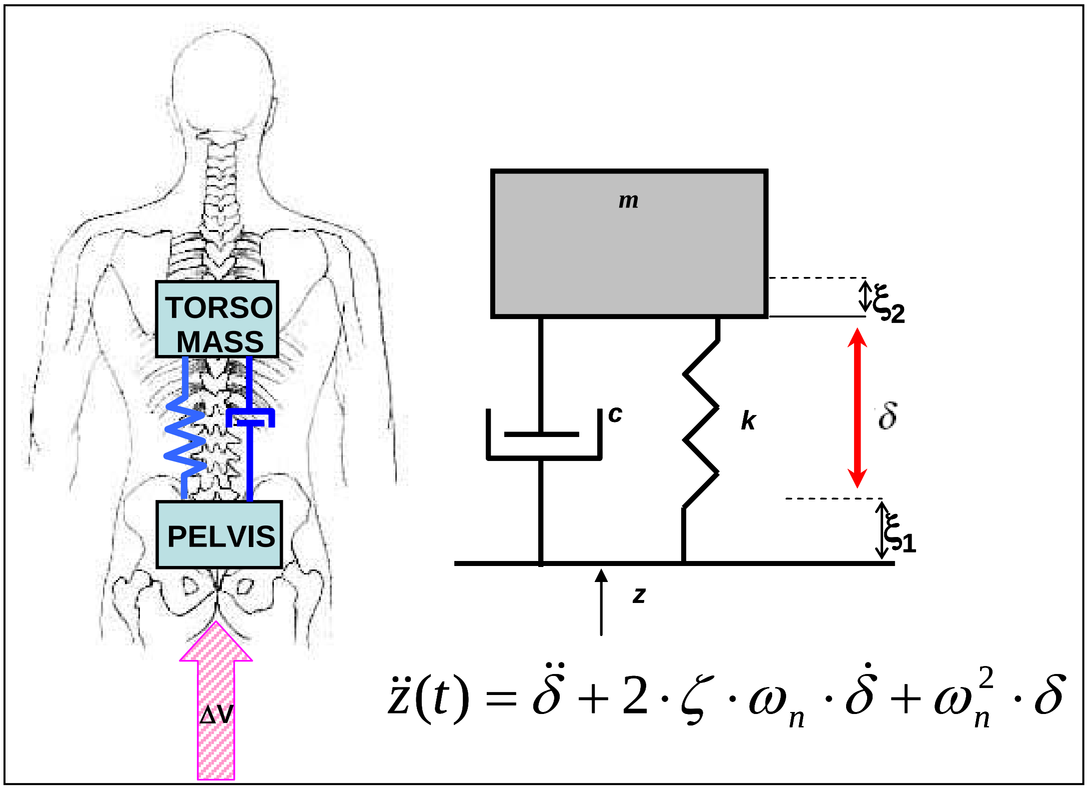

Figure A-1. The single degree of freedom model of the human spine.

The DRI model is a measure of spine compression, δ, that correlates well with spine compression injuries in ejection seat accidents. The model is widely used in the mine blast survivability studies. The index is calculated by

$$DRI = \frac{\omega_n^2 \delta_{\max}}{g}, \tag{A-1}$$

where ω is 8.4 Hz, ξ is 0.224, and g is 9.8 m/s^2. The experimentally determined logistic regression defines the limit of the DRI at 17.7, corresponding to a 10% likelihood of moderate injury (figure A-2).

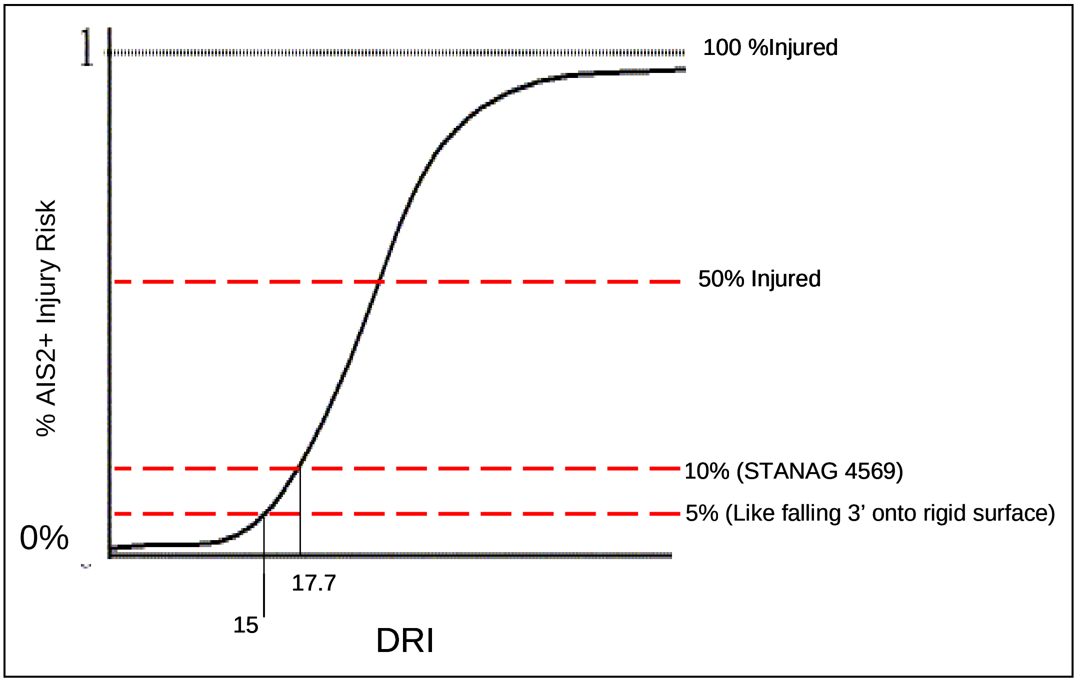

Figure A-2. Logistic regression of injury risk percent vs. DRI value.

Appendix B. Result Time Histories

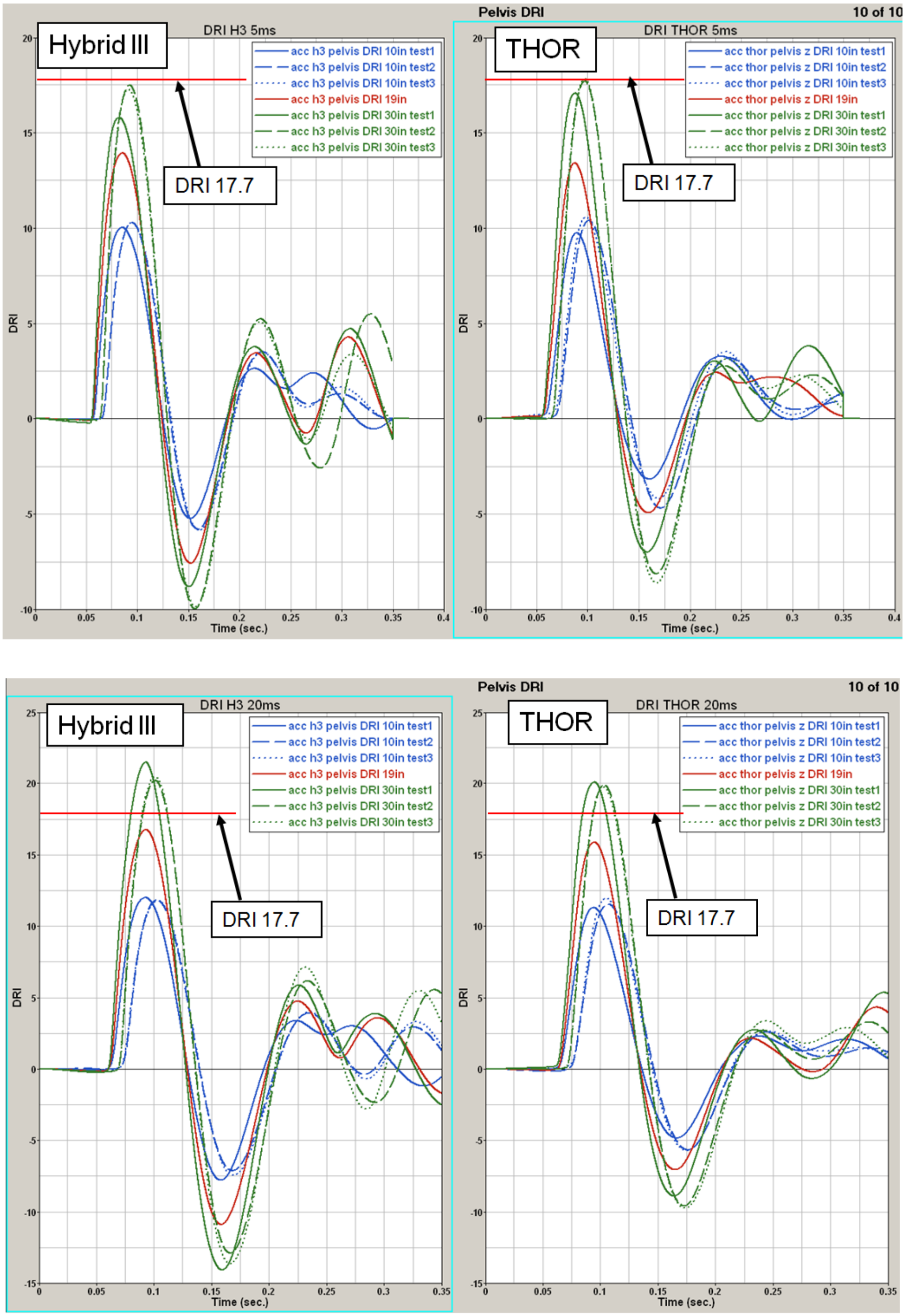

Figure B-1. Pelvis DRI_z, 5- and 20-ms pulse duration.

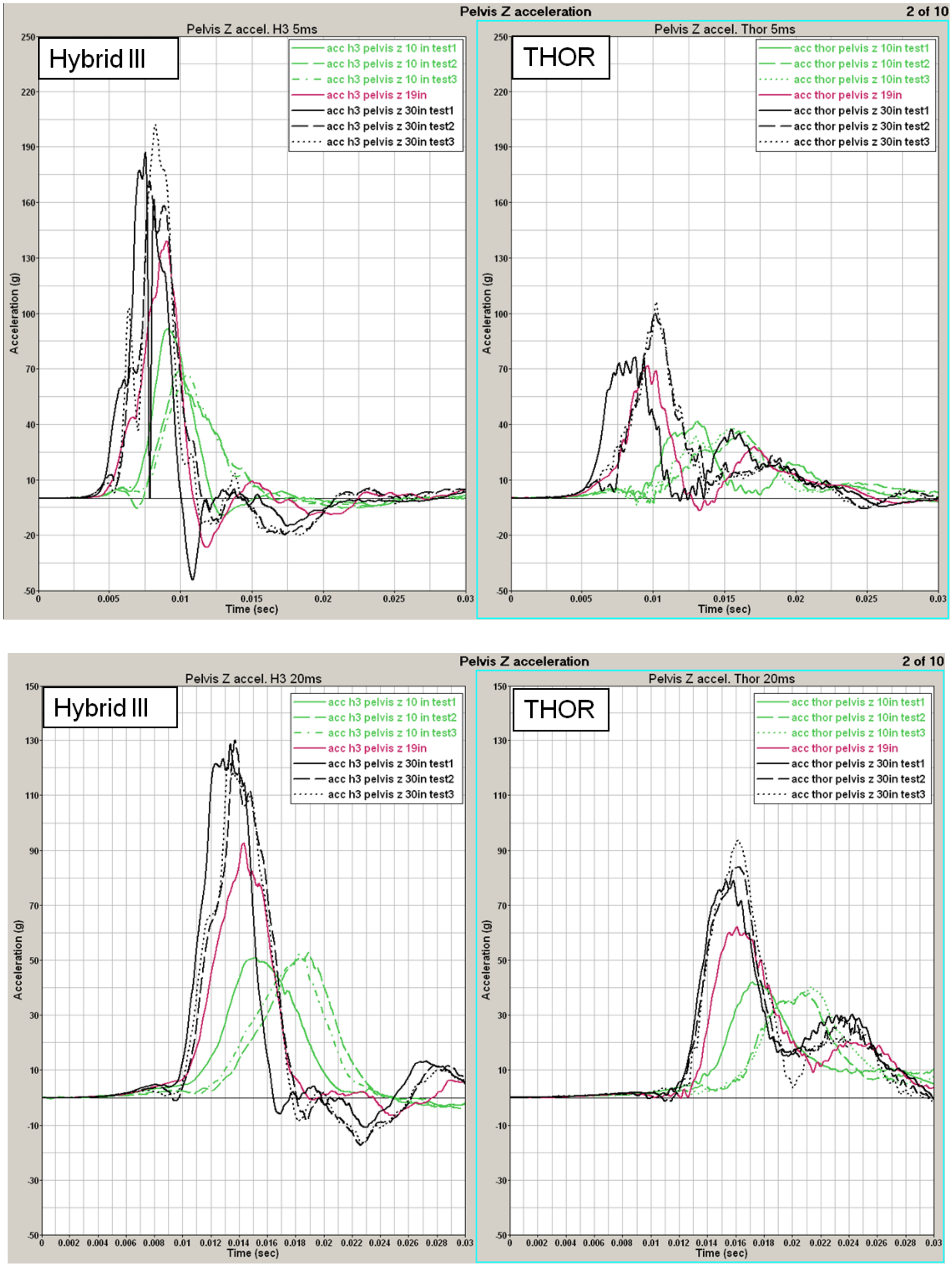

Figure B-2. Pelvis Z acceleration, 5- and 20-ms pulse duration.

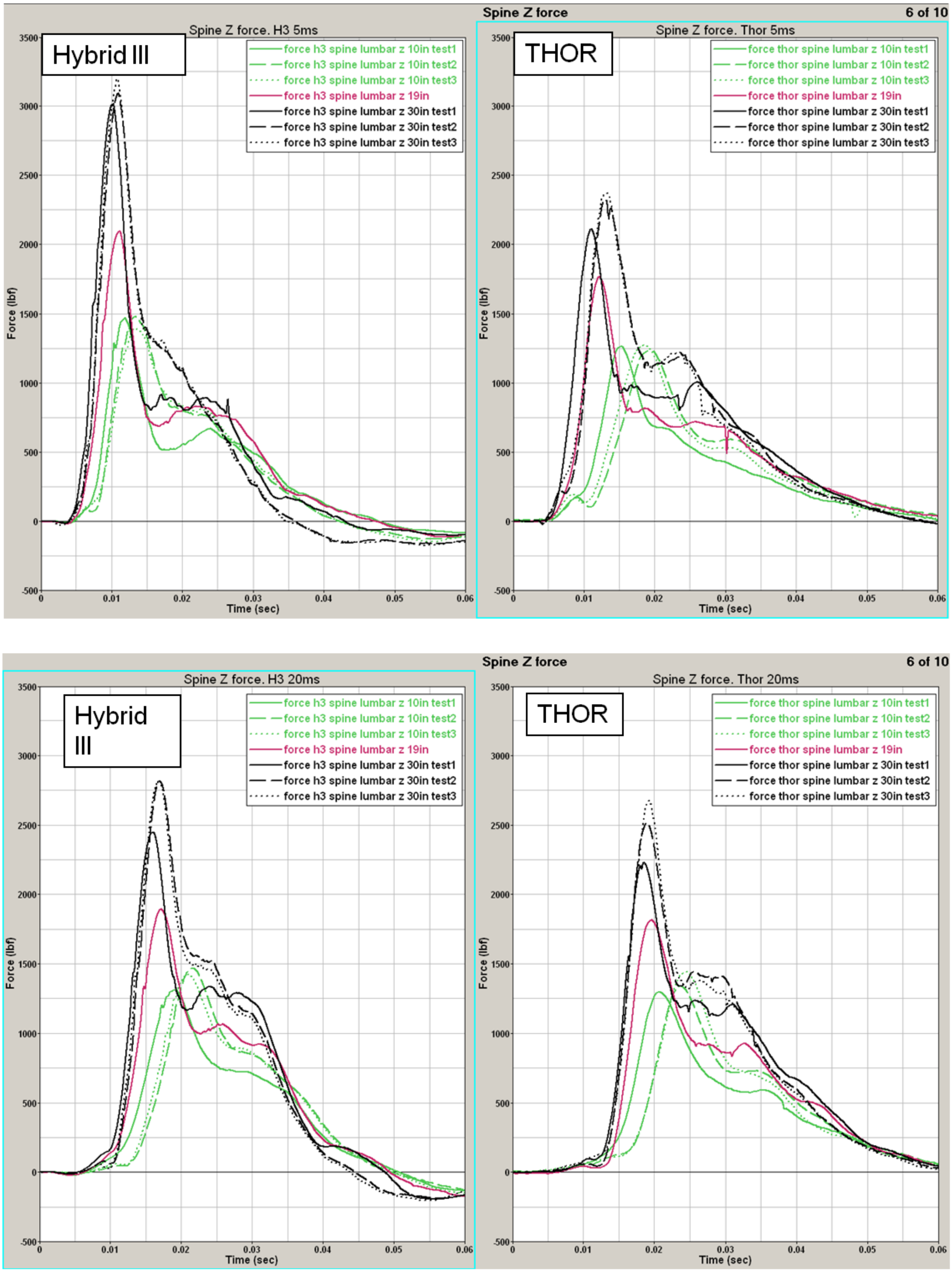

Figure B-3. Spine Z force, 5- and 20-ms pulse duration.

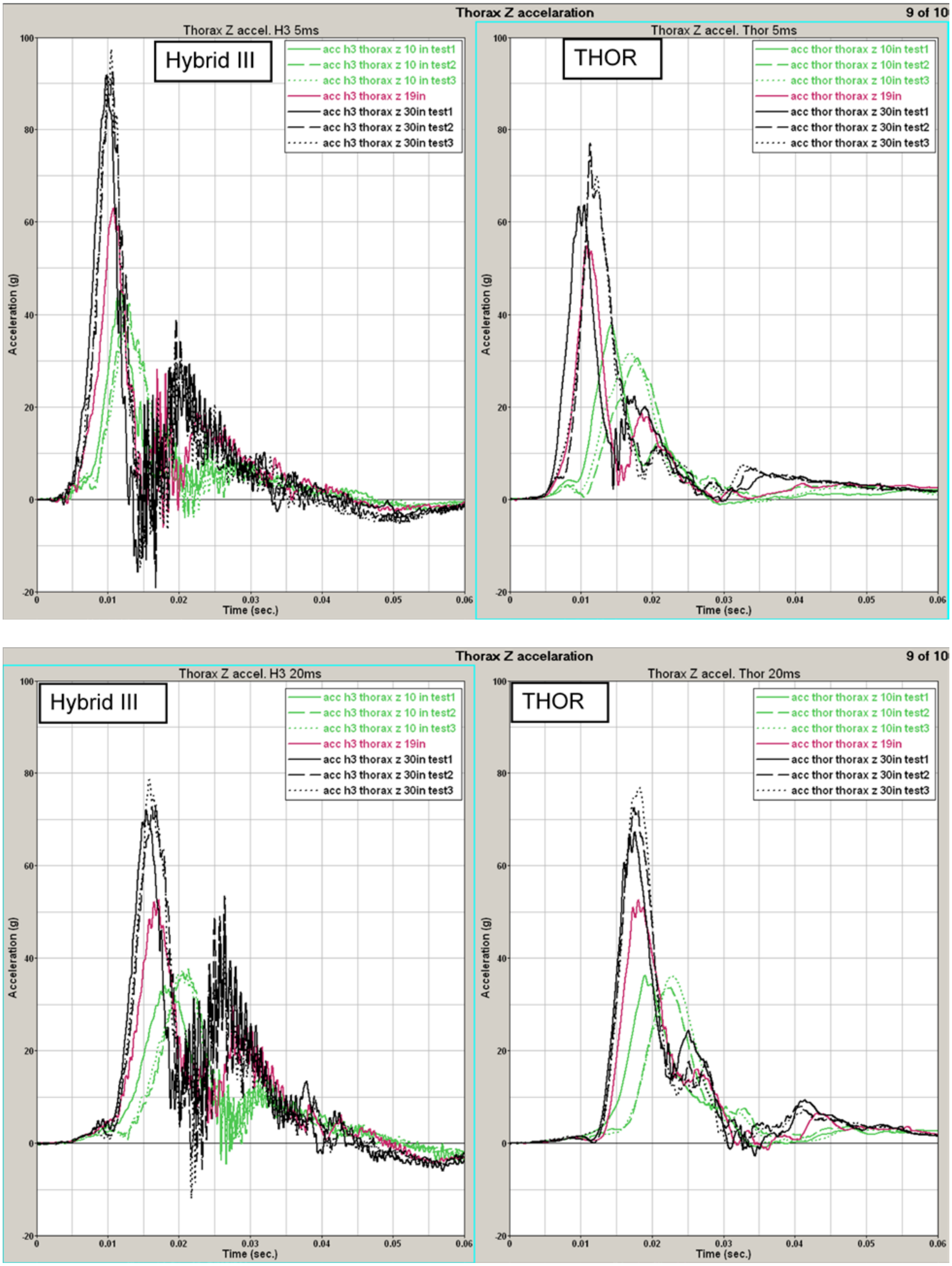

Figure B-4. Thorax Z acceleration, 5- and 20-ms pulse duration.

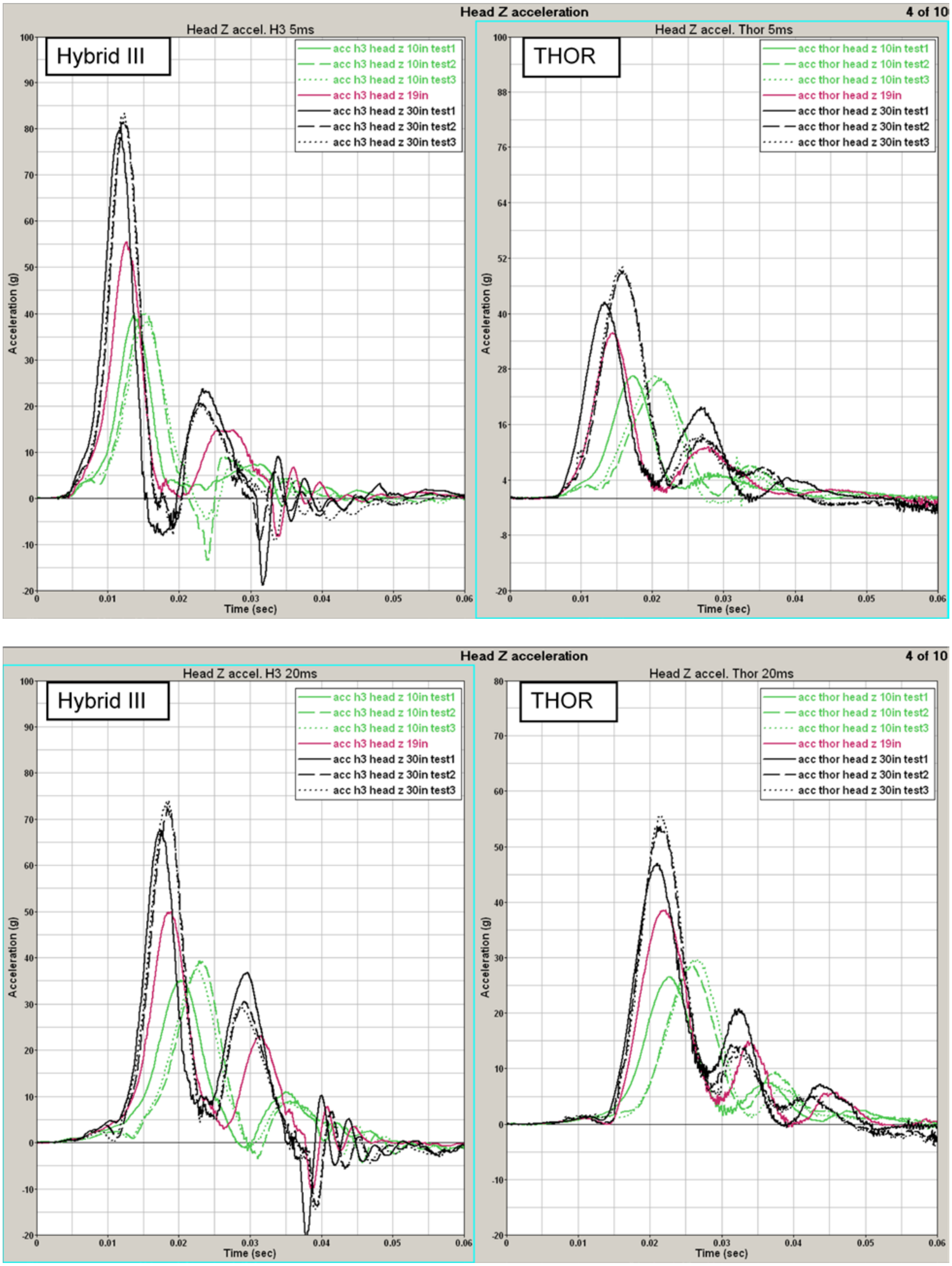

Figure B-5. Head Z acceleration, 5- and 20-ms pulse duration.

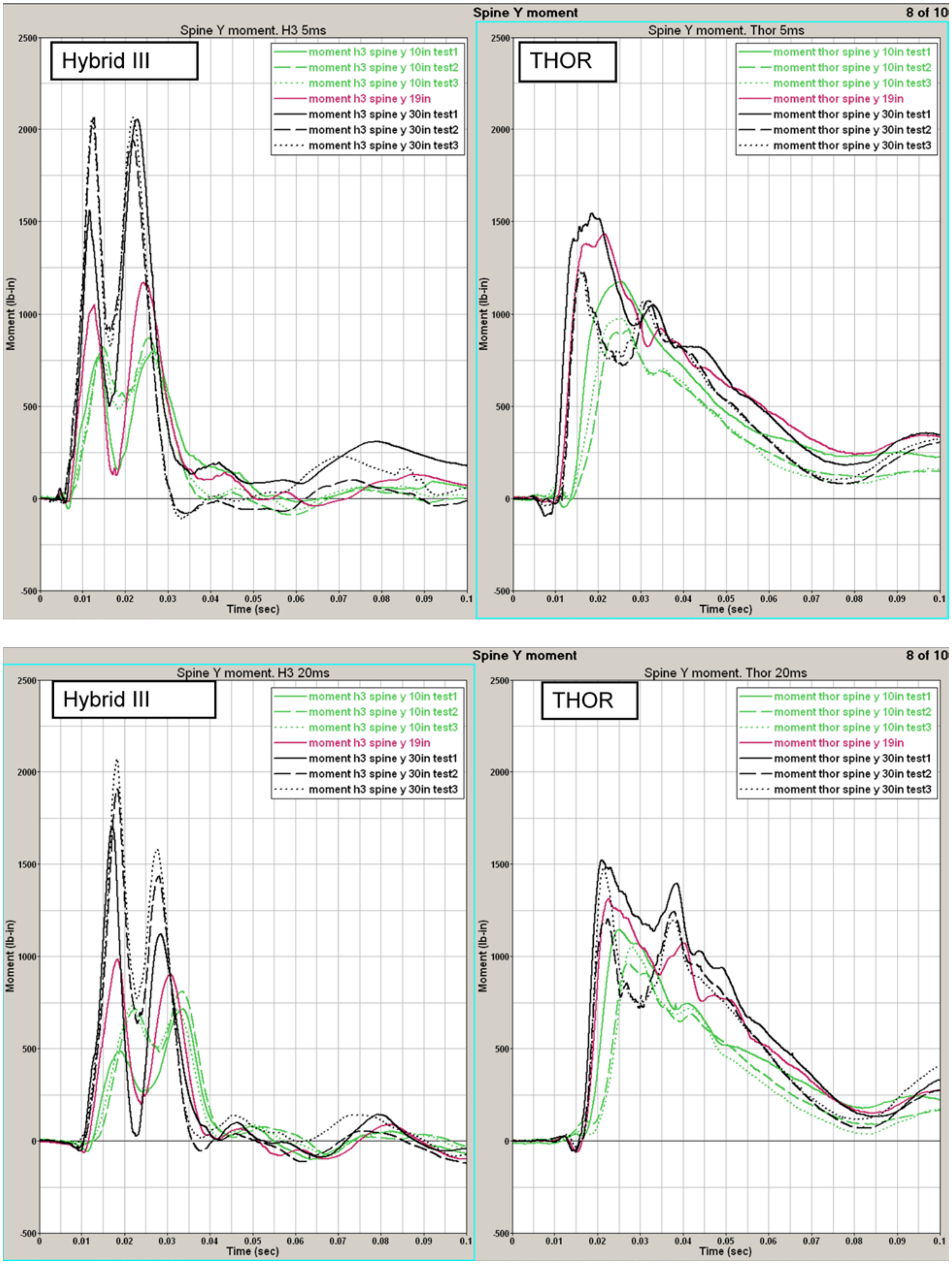

Figure B-6. Spine Y moment, 5- and 20-ms pulse duration.

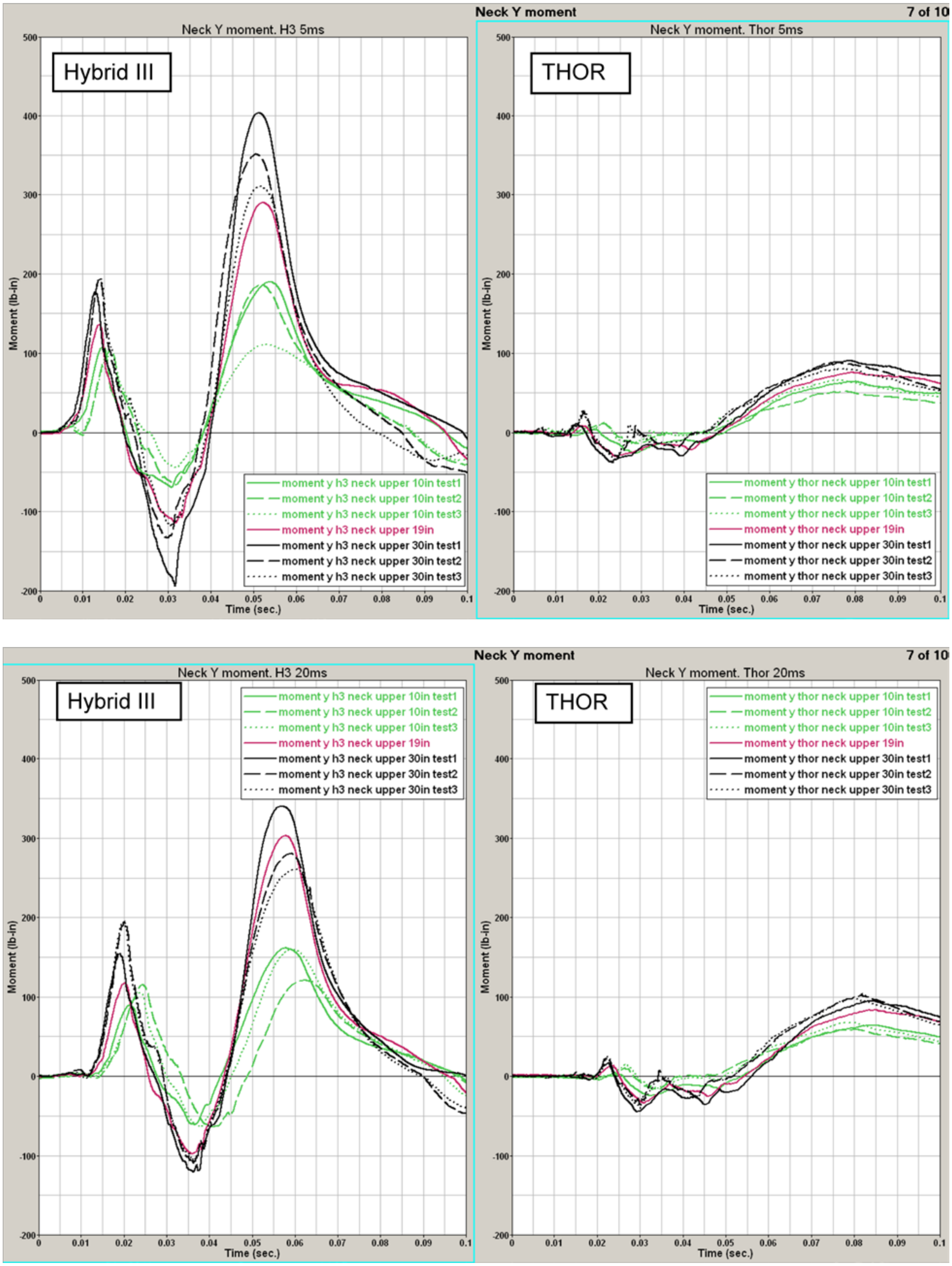

Figure B-7. Neck Y moment, 5- and 20-ms pulse duration.

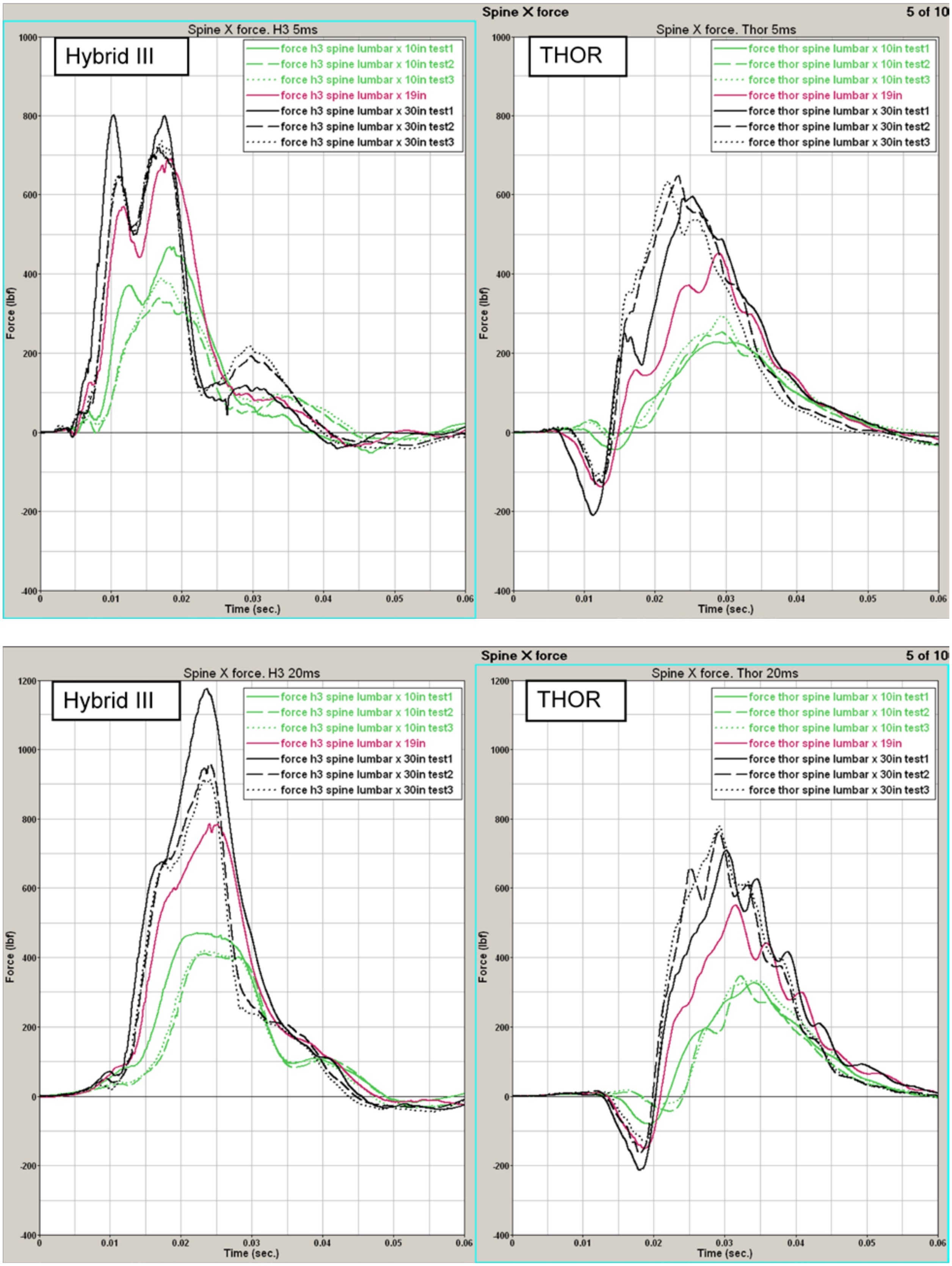

Figure B-8. Spine X force, 5- and 20-ms pulse duration.

List of Symbols, Abbreviations, and Acronyms

ARL	U.S. Army Research Laboratory
ATD	anthropomorphic test device
A_z	acceleration time history
DRI_z	dynamic response index
NHTSA	National Highway Traffic Safety Administration
PMHS	post mortem human subjects
PVC	polyvinyl chloride
THOR	Test Device for Human Occupant Restraint
ΔV	velocity change

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